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Spin-controlled negative magnetoresistance resulting from exchange interactions

N. V. Agrinskaya[1)], *V. I. Kozub, N. Yu. Mikhailin, D. V. Shamshur*

A.F. Ioffe Institute, 194021 Saint Petersburg, Russia

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We studied conductivity of AlGaAs-GaAs quantum well structures (where centers of the wells were doped by Be) at temperatures higher than 4 K in magnetic fields up 10 T. Throughout all the temperature region considered the conductivity demonstrated activated behavior which is in accordance to concept of virtual metal-insulator transition we have suggested earlier [1–3]. Namely, we believe that in the narrow impurity bands existing in situations of a weak disorder (in particular, due to low compensation degree) the band of delocalized states is formed near the center of the band at concentrations significantly smaller than characteristic for standard Anderson transition. At the same time the weak compensation implies that the Fermi level is situated in the bandtail, that is outside of the band of delocalized states. As a result, the non-zero conductivity is possible only due to activation of the carriers from the Fermi level to the mobility edge.

At moderate magnetic fields $0.1\,\mathrm{T} < H < 1\,\mathrm{T}$ we observed negative isotropic magnetoresistance which was linear in magnetic field while for magnetic field $H > 2\,\mathrm{T}$ the magnetoresistance is anisotropic as it is expected for 2D structures. Namely, for magnetic fields normal with respect to the plane of the wells the magnetoresistance was positive. To the best of our knowledge, it was the first observation of linear negative magnetoresistance which would be isotropic with respect to the direction of magnetic field. The isotropic character of magnetoresistance apparently evidences role of spins. The spin effects in hopping conductance were widely discussed earlier (see, e.g. [4–7]). However, in our case corresponding to some temperature region the most important contribution is related to activation of localized carriers to the region of delocalized states. The typical experimental picture of isotropic magnetoresistance is given at Fig. 1.

As it is seen, the latter is negative and linearly increases with the field increase. The similar behavior was observed for other samples. We emphasize that the behavior in question was correlated with activated behavior of conductivity observed at rather broad temperature region and to a breakdown (which we relate to impact ionization of localized states by delocalized carriers, see [3]) observed for the same samples at significantly lower temperatures or at significantly higher currents.

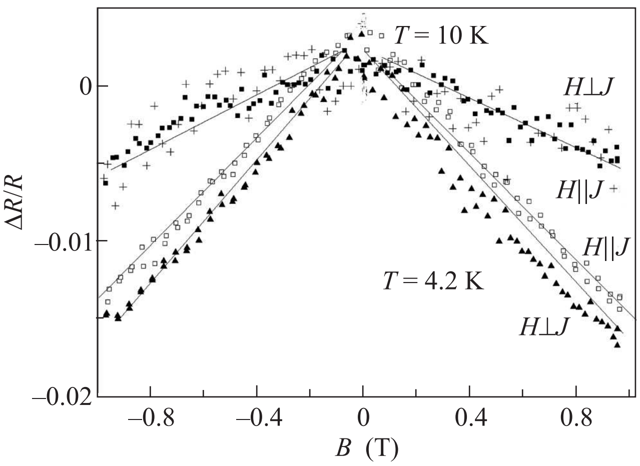

Fig. 1. Magnetoresistance of sample 1 at 4.2 K and 10 K

Thus the data presented here for doped 2D structures of GaAs-AlGaAs quantum wells allows to emphasize two experimental facts: (i) temperature behavior of the conductivity demonstrates activation behavior with small activation energies; (ii) magnetoresistance for low temperatures and low magnetic fields demonstrates linear field dependence and does not depend on the field direction.

The isotropic negative magnetoresistance needs an additional analysis. As it is known, linear negative magnetoresistance in hopping regime is typically explained as resulting from the interference contribution due to an interference between the "direct" hop and of the hopping trajectories involving an intermediate center of the underbarrier scattering [8]. However, in this case the magnetoresistance is controlled by a magnetic flux through the area restricted by the trajectories mentioned above. Thus, in 2D structure it depends only on the field component normal to the plane of 2D electron structure. Thus such (an orbital) mechanism fails to explain the

1)e-mail: nina.agrins@mail.ioffe.ru

experimentally observed behavior. At the same time the isotropic character of the magnetoresistance motivates us to consider possible spin mechanisms which are not expected to be dependent on the field direction. The natural spin effect on the site energies is related to the Zeeman energy. However, the earlier theoretical studies of magnetoresistance (including transport over delocalized states) resulting from the direct effect of Zeeman splitting (see, e.g., [4–7, 9–12]) fail to explain the behavior observed in our experiments.

To our opinion, the important factor which can emphasize the spin effects in conductivity is related to a contribution of exchange interactions between the localized carriers to the structure resistance. In particular, these (spin-dependent) interactions facilitate the effect of spin polarization on the site energies.

First, we would like to note that the disorder in exchange interaction energies (resulting from spin disorder) affect the scatter in site energies. In its turn, the resistance is sensitive to such a scatter which leads to a specific spin mechanism of magnetoresistance. Namely, the partial ordering introduced to spin subsystem by the magnetic field can lead to partial suppression of disorder related to exchange contribution of the site energies. The latter can lead to a decrease of the width of the impurity band. Since the positions of the chemical potential and of the mobility edge are both dependent on the width of the impurity band, one expects that a decrease of this width can lead to a decrease of the energy needed for activation from the Fermi level to the mobility edge and thus to decrease of the resistance. Such an effect can take place along different scenarios. However, the conventional considerations seem to give non-zero weak field effect only in quadratic (in magnetic field) approximation. Indeed, one can discriminate between 3 different energies: (i) magnetic field induced variation of the site energy, δE_i; (ii) exchange interaction between different on-site spins, J_{ij}; (iii) temperature T. In our experiments we definitely have $\delta E_i < T$, and, most probably, $\delta E_i < J_{ij}$ (although the last inequality is not so clear). As for the relation between δE_i and T, we note, that for $\delta E_i < T$ the standard statistical analysis of the possible effect related to the systematic addition δE_i to (random) quantity E_i leads to only quadratic (in δE_i) corrections to the variance of E_i. If the system is close to the spin glass configuration (which is expected for systems close to metal-insulator transition), then J_{ij} from statistical point of view plays a role of "effective temperature" and thus, again, only quadratic corrections in terms of δE_i seem to be expected.

To exclude possible effects which could be related to ferromagnetic spin order within the systems, we studied the Hall effect up to the fields 14 T. No traces of the anomalous Hall effect were found which allows to exclude the corresponding spin ordering.

Thus, to understand the nature of the puzzling linear negative magnetoresistance observed in our experiments further detailed theoretical efforts are needed. In particular, we would like to note several factors which until now have not obtained proper considerations. (i) To estimate the magnetic-field dependent contribution to the variance of the on-site exchange energies the detailed analysis of spin statistics in site aggregates is needed. (ii) To the best of our knowledge, the effect of spin on the position of the mobility edge still had not been considered in any detail. (iii) The picture of magnetoresistance can be sensitive to spin flip processes in course of activation of carriers from the Fermi level to mobility edge (provided such processes are effective). (iv) We can also expect that the contribution of exchange interactions in close site pairs (similar to those participating in Bhatt–Lee phase [13]) can be important for the effect of magnetic field on the width of the impurity band. We are going to consider these factors in detail elsewhere.

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